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LIQUID HYDROGEN TURBOPUMP RAPID START PROGRAM

MONTHLY PROGRESS REPORT No. 20

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SUMMARY

The effort during the past month has been directed toward the completion of the coated feed system testing and data analysis of both the uncoated and coated system tests. Writing of the final report was also initiated.

A total of eleven tests were conducted with the coated feed system during three days of testing. Chill data was acquired for thermal conditioning of the system from ambient initial conditions using a duct inlet propellent pressure of 72 psig. A comparison with the respective uncoated system test indicates the coating resulted in a significant reduction in the time required for propellant temperatures at the pump inlet and exit to reach saturated conditions.

After three tests to determine steady-state pump performance and nominal start transient operation, three coated system turbopump starts were attempted with various degrees of pre-chill. Although not acutally demonstrated in testing, data analysis indicates it may be possible to start the turbopump in less than ten seconds after chill flow is initiated. This start time could probably be realized with an inlet pressure of 65 psig if the start sequence used in testing were modified.

Finally, four deadhead pump starts were attempted with a downstream volume of 3.45 cubic feet and discharge pressures of 600, 500 and 400 psig initiating opening of the downstream throttle valve. The uncoated pump started with all three of these "trigger" pressures, but only the lowest pressure was successful with the coated system. Due to the degradation in pump performance caused by the coating, the two highest trigger pressures exceeded the discharge pressure achievable at nominal speed.

Upon conclusion of these tests, the coated inlet line and pump were removed from the test stand, visually inspected and placed in storage. With very minor exceptions and some larger pieces which were broken loose by flexing the inlet line bellows during removal, the superficial inspection indicated the coatings stayed on extremely well.

INTRODUCTION

The purpose of this program is to design and develop a liquid cryogen turbomachinery that can achieve rapid starts with minimum thermal preconditioning and with increase in payload potential and mission flexibility of the Space Shuttle vehicle. Such turbomachinery could have particular application in the auxiliary propulsion system (APS) where minimum and random starts are required.

Propellant feed system chilldown time can be reduced through the use of coatings. Previous contracted efforts (NAS8-20167 and NAS8-20324) have demonstrated improved line chilldown efficiency, material compatibility and application techniques for turbomachinery. Additional effort needs to be performed to define design features and control or functional parameters that promote rapid start transients, minimize propellant losses and upgrade performance of adjacent subsystems.

The potential advantages for utilizing coated propellant pumps are the minimizing of chilldown losses, simplifying pump start requirements and increased system operating flexibility. Rapid pump starts, particularly in an APS application suggest turbomachinery design and controls that provide a "deadhead" start capability. The relationship between a deadhead start and the degree of pump chilldown is presently unknown.

The objective of this program will be to develop data on a typical auxiliary propulsion hydrogen feed system to determine the interrelationship between feed system coatings, chilldown time, deadhead starting, minimum start times, feed system geometry, and control functions.

DISCUSSION

TASK III

Data analysis of the uncoated feed system tests was completed. These tests were discussed in the quarterly report last month and will not be reiterated at this time. Documentation of these tests for the final report has been initiated.

TASK IV

A total of eleven tests with the coated feed system were conducted between 4 April and 9 April. The system was chilled from ambient initial conditions three times. The first of these tests was to obtain chill data and utilized ducting and instrumentation calibrations suitable for achieving accurate data under low flow conditions. The inlet duct propellant puressure for this test was approximately 72 psig. The pump inlet and exit propellant temperatures for this test are compared with those for an uncoated feed system with an inlet duct pressure of approximately 75 psig in Figs. 1 and 2. As shown, the coatings significantly reduce the time required for these temperatures to reach saturated conditions.

Three tests were conducted to determine the steady-state pump performance and establish the nominal start transient. The coated pump develops approximately twenty percent less head than the uncoated one for a given flow and speed.

Turbopump start tests were also conducted with three different degrees of pre-chill. These tests differed from those run previously in that both downstream ducts, i.e., those used for chill and start tests, were open

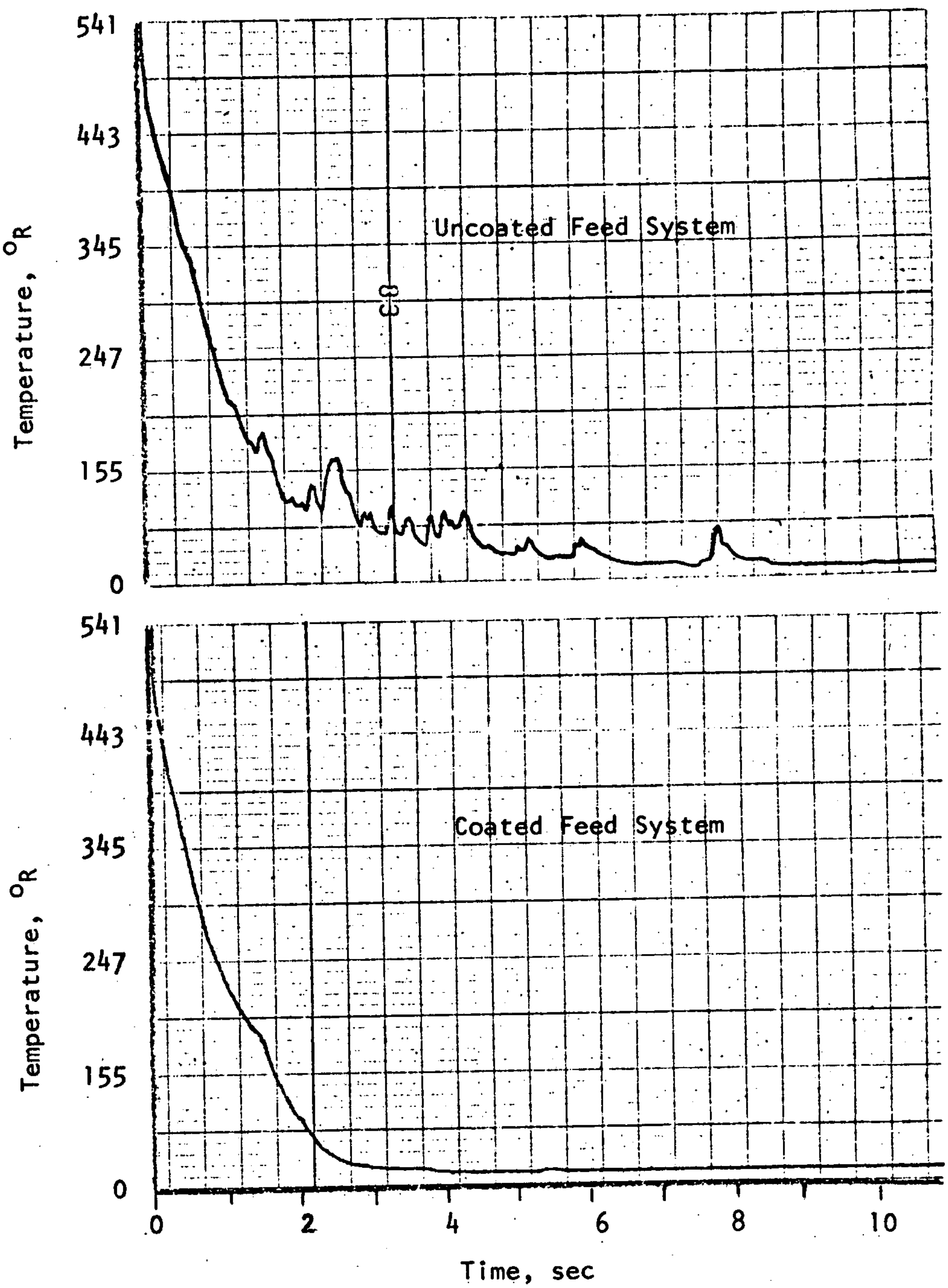

Figure 1. Pump Inlet Hydrogen Temperature Transient

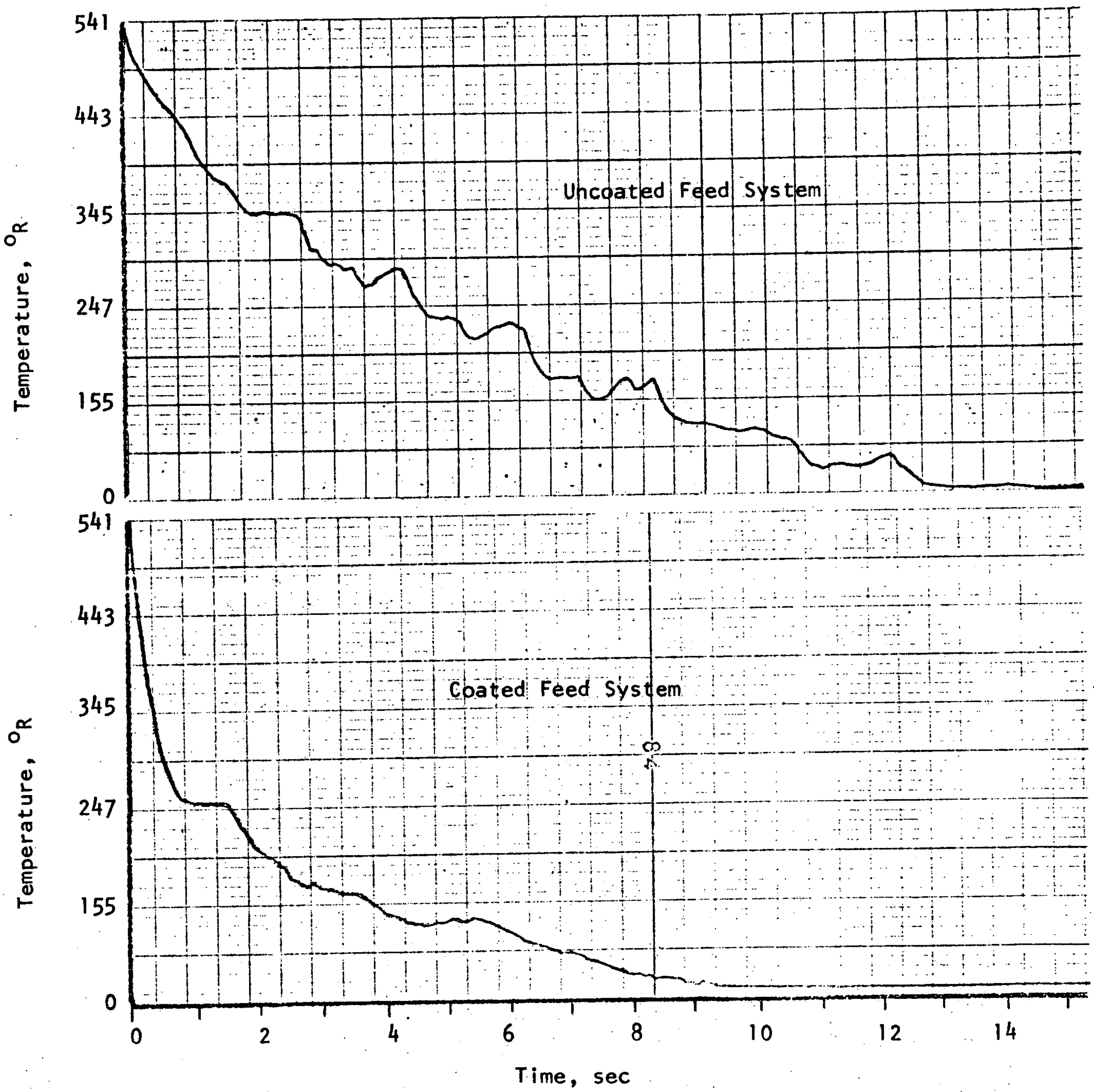

Figure 2. Pump Exit Hydrogen Temperature Transient

during pre-chill. Figure 3 shows a flow schematic. With the emphasis on starting in the shortest possible time, it was decided to flow through the chill-test ducting during pre-chill because of its low resistance. Rather than try to open the throttle valve during turbopump acceleration, the throttle valve was also open during pre-chill. Since the chill-test ducting had not been used at high pressures and the throttle valve position had not been calibrated with the chill system valve open, it was necessary to close the chill system valve prior to turbopump rotation. This sequencing was done manually.

The results of the first test, chilled from ambient initial conditions, are shown in Figs. 4a through 4e. Pump speed accelerates very rapidly to 30,000 rpm and an automatic cut is initiated (Fig. 4a). Pump pressure rise is negative prior to rotation (Fig. 4b). At approximately ten seconds the pressure drop through the pump is reduced because the flow is reduced when the chill system valve is closed. A pump pressure rise of approximately 100 psi is achieved during rotation. A chill flow of approximately 80 gpm is established before the chill system valve is closed; but, afterwards, this value is cut in half (Fig. 4c). The very high peaks in flow indicated by the turbine-type flowmeter are due to vapor. The pump inlet hydrogen temperature steadily decreases to less than 50^{o}R before the chill system valve is closed; but, afterwards, heated vapor is generated by residual duct heat (Fig. 4d). Vapor is present when pump rotation is initiated. The pump exit temperature steadily decreases to less than 40^{o}R before the chill system valve is closed, but heated vapor is generated afterwards (Fig. 4e). The lower temperature at the pump exit than at the inlet is due to the lower pressure. Vapor is present when pump rotation is initiated.

Results from the second test are presented in Figs. 5a through 5e. This test followed a previous chill rather than being at ambient initial

SEQUENCE

1. Open valve in chill system discharge line (chill system valve).
2. Open valve in start system discharge line (throttle valve).
3. Open valve in inlet line (inlet valve).
4. Close chill system valve.
5. Open valve in turbine inlet line (turbine valve).
6. Automatic turbine overspeed cut initiated (30,000 rpm).

SCHEMATIC

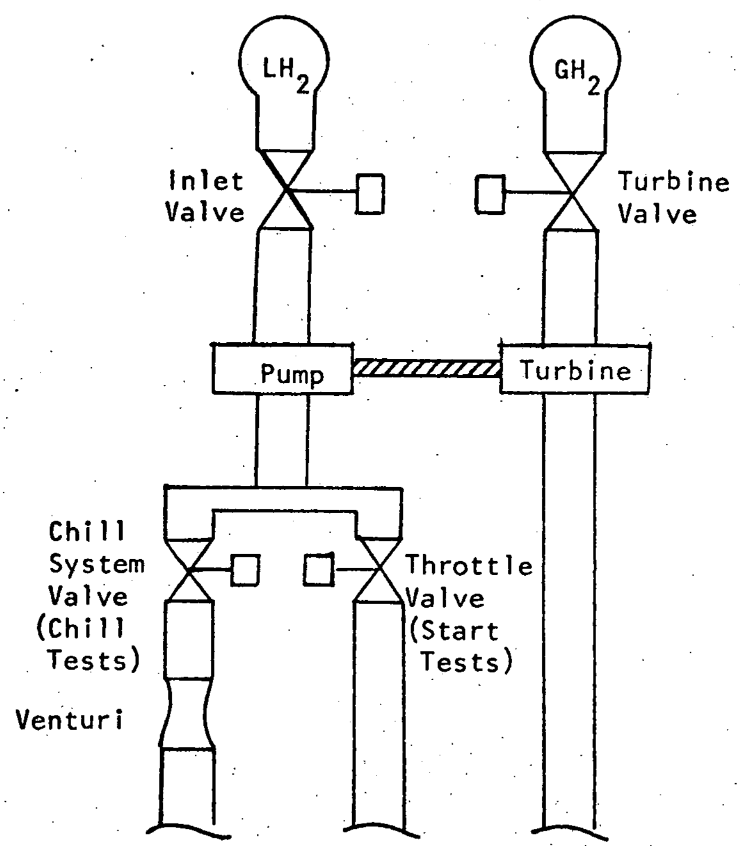

Figure 3. Test Sequence and Schematic

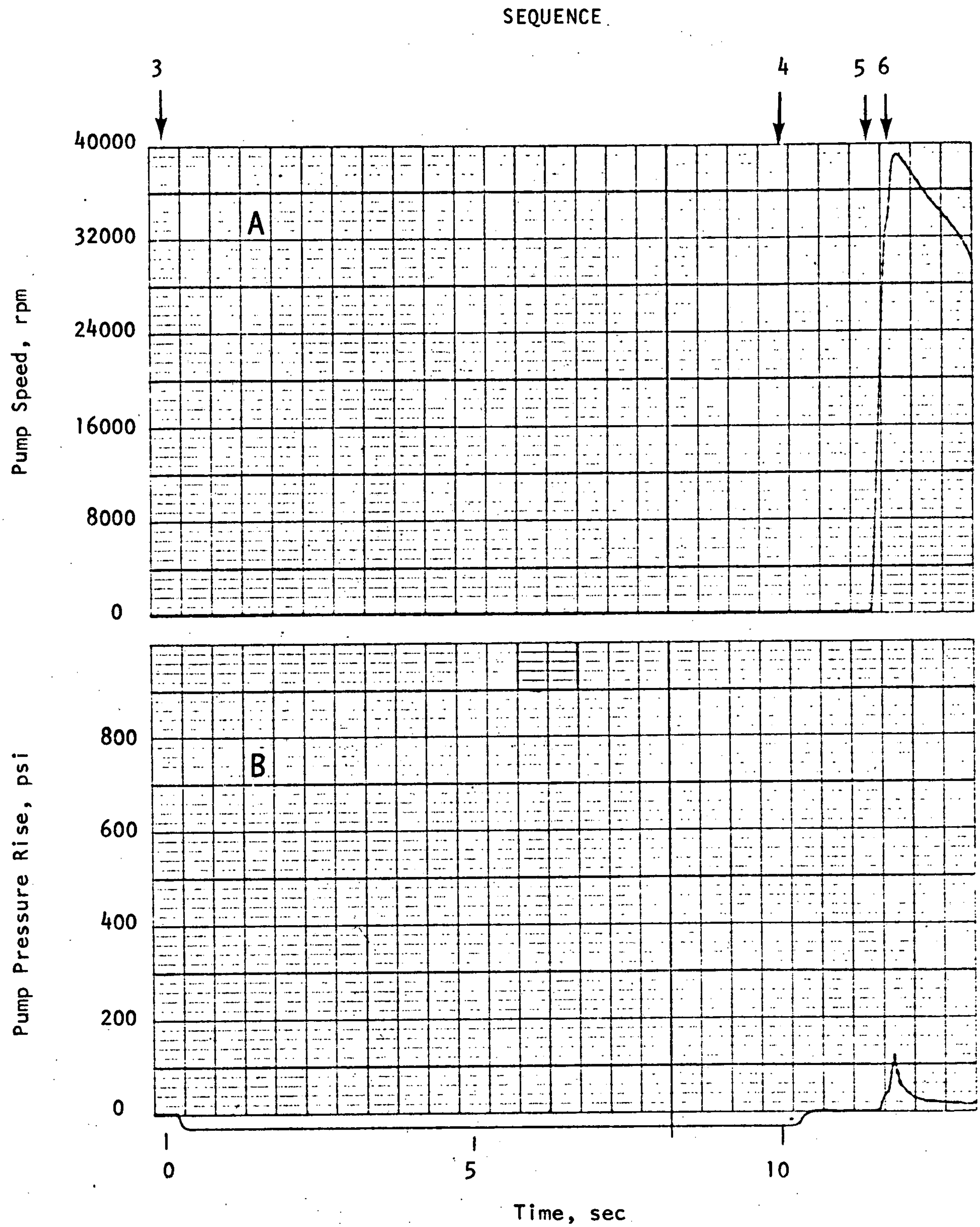

Figure 4. Transients For First Partial-Chill Test

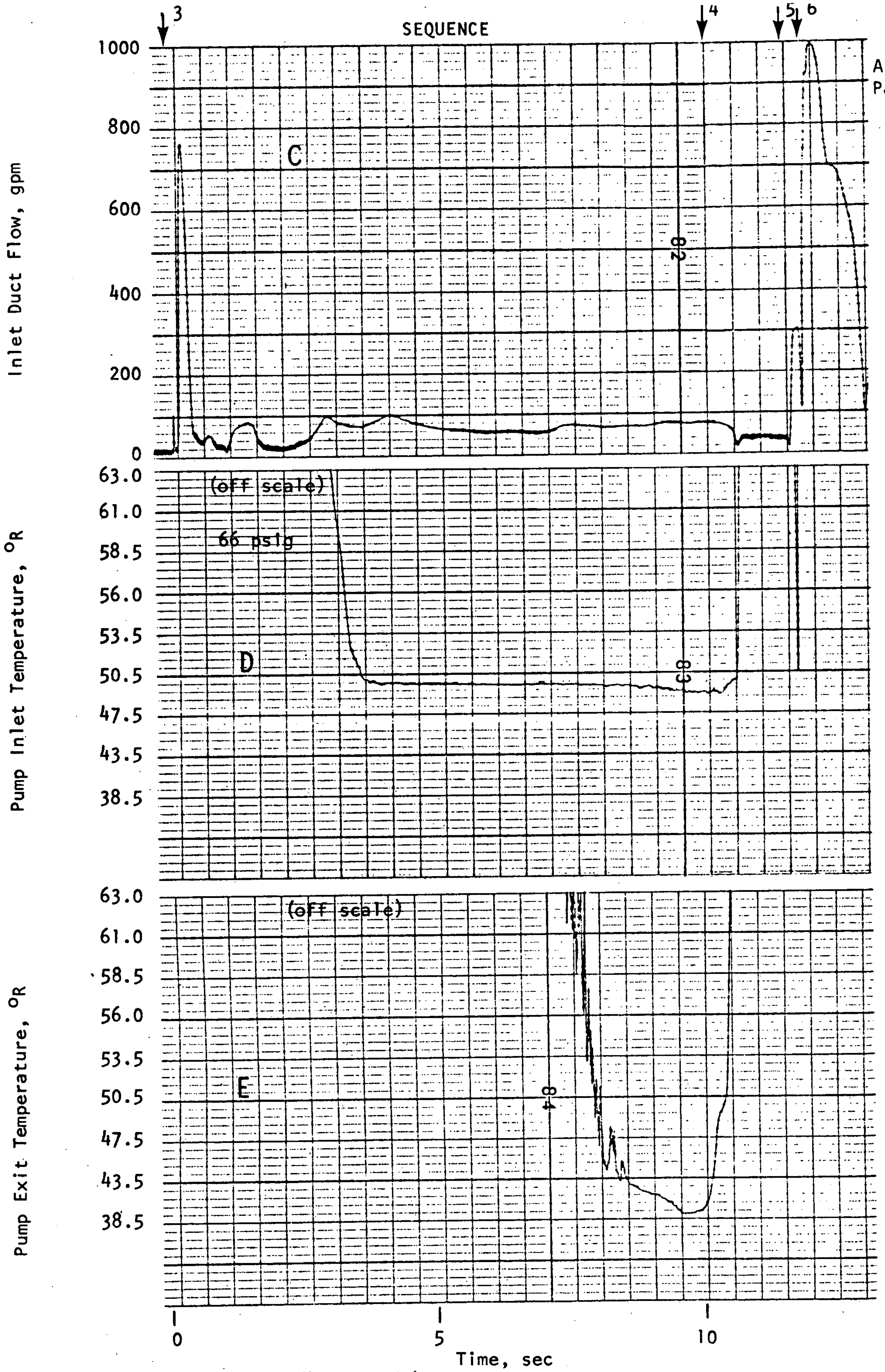

Figure 4 (continued)

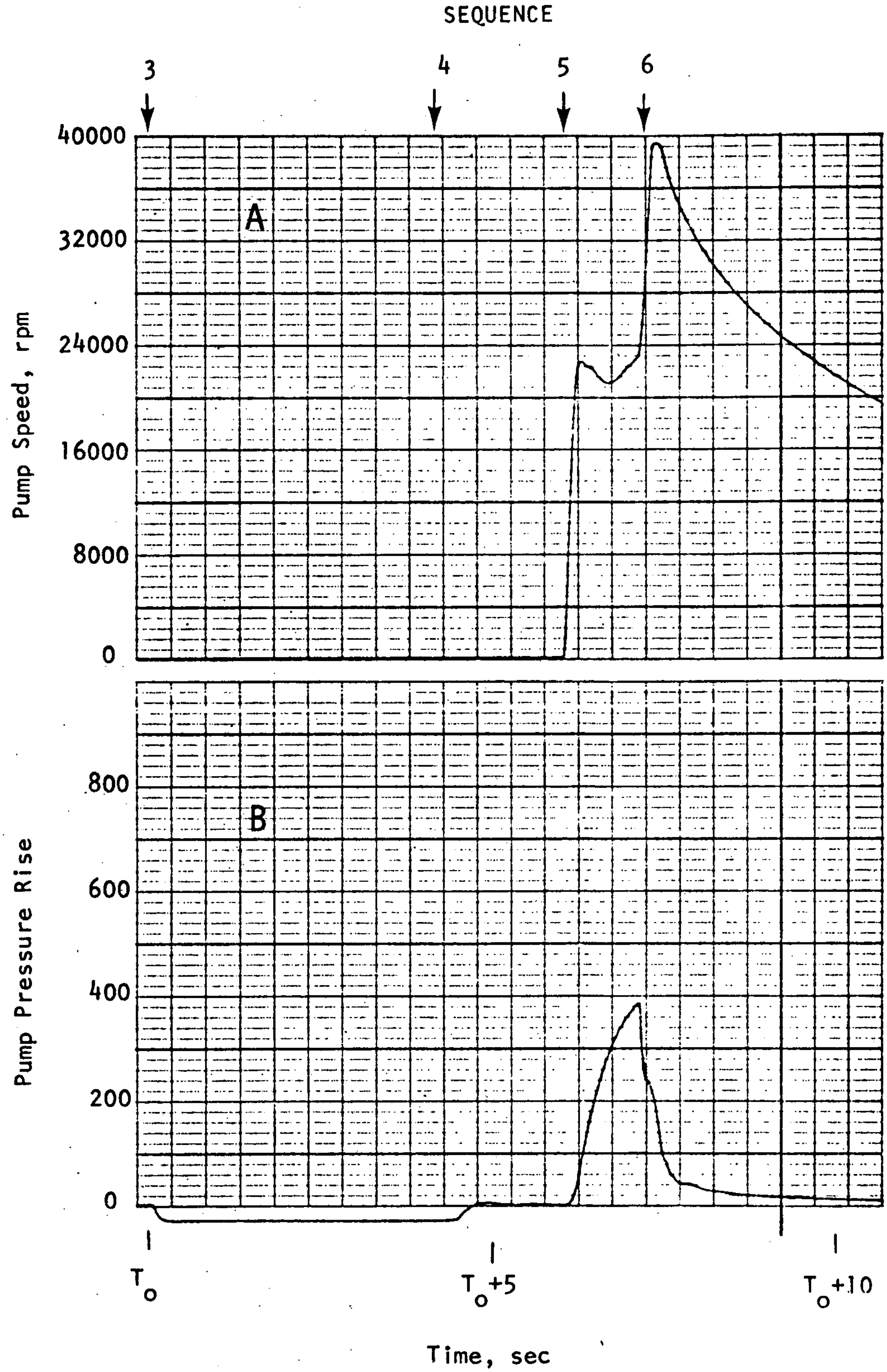

Figure 5. Transients For Second Partial-Chill Test

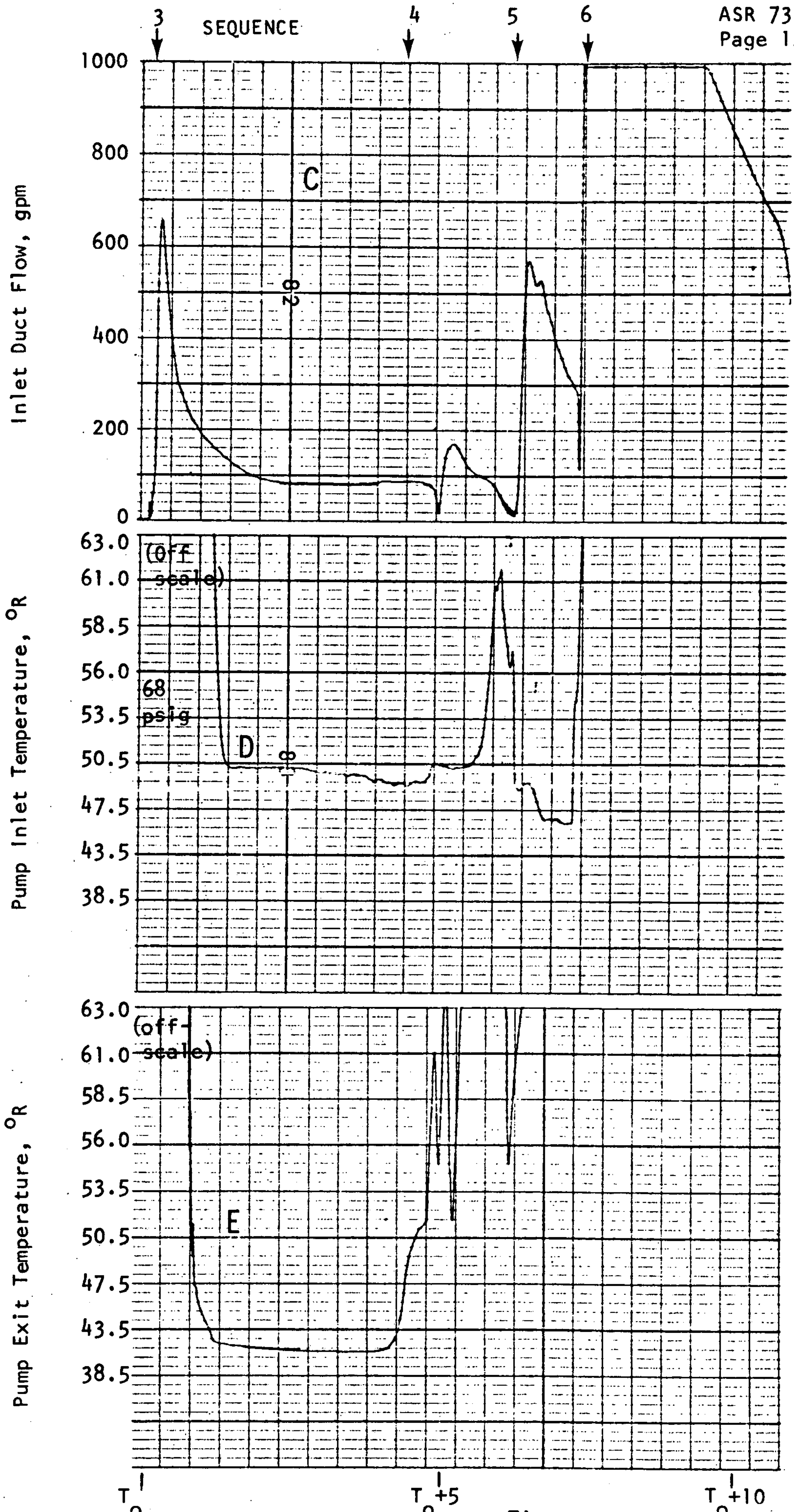

Figure 5 (continued)

conditions and therefore absolute times should not be compared with the previously discussed test. The pump accelerated to approximately 22,000 rpm and leveled off for one second before a breakdown in developed head occurred (Fig. 5a). A pump pressure rise of nearly 400 psi was developed before breakdown (Fig. 5b). After a steady chill flow of 80 gpm, the flow decreased (after an initial oscillation) when the chill system valve was closed (Fig. 5c). Hydrogen temperature at the pump inlet was less than 50°R before the chill system valve was closed; but, afterwards, the lower chill flow caused the inlet temperature to spike to over 60°R and undoubtedly pockets of heated vapor were generated in the inlet duct (Fig. 5d). This was a less severe condition than observed in the previous case and indicates a more fully chilled system. The pump exit temperature was 41°R before the chill system valve was closed; but, after oscillating, went off scale after the valve was closed (Fig. 5e).

The results of the third test, which started successfully, are shown in Figs. 6a through 6e. This test also followed a previous chill and absolute times are not meaningful. The pump speed transient was very smooth and settled out at 22,000 rpm (Fig. 6a). The pump pressure rise was 450 psi (Fig. 6b). The chill flow gradually increased from 80 to 180 gpm before the chill system valve was closed (Fig. 6c). Afterwards, the chill flow decreased to 40 gpm. A normal flow transient was then indicated during turbopump start. The pump inlet temperature decreased to 44°R before the chill system valve was closed, but then jumped to almost 50°R after the valve was closed (Fig. 6d). This temperature trace indicates this test to be the most chilled of the three. The pump exit temperature decreased to less than 40°R before the chill system valve was closed, but then increased to 50°R after closure (Fig. 6e). Upon initiation of pump rotation, the exit temperature increases due to pump inefficiency.

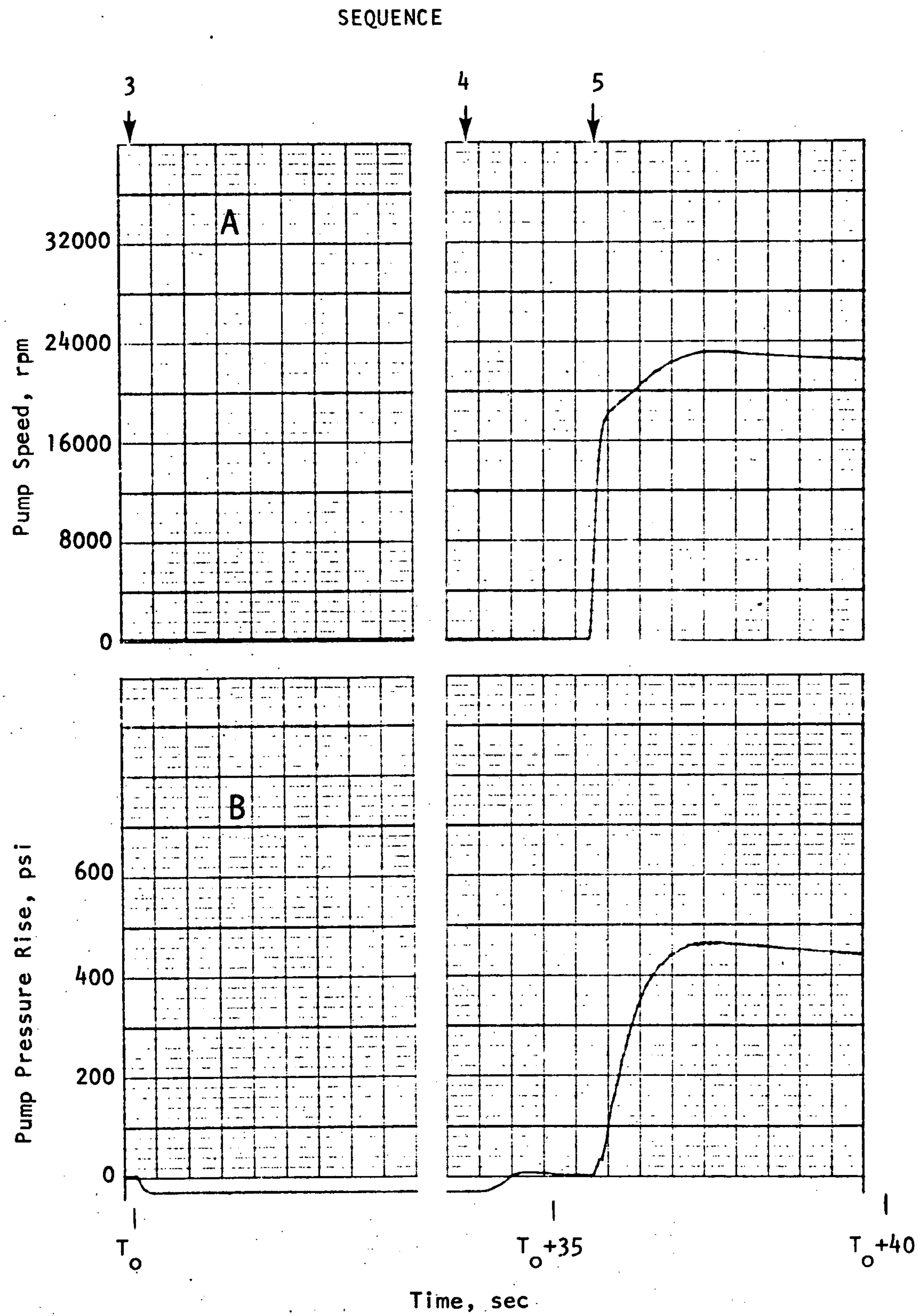

Figure 6. Transients For Third Partial-Chill Test

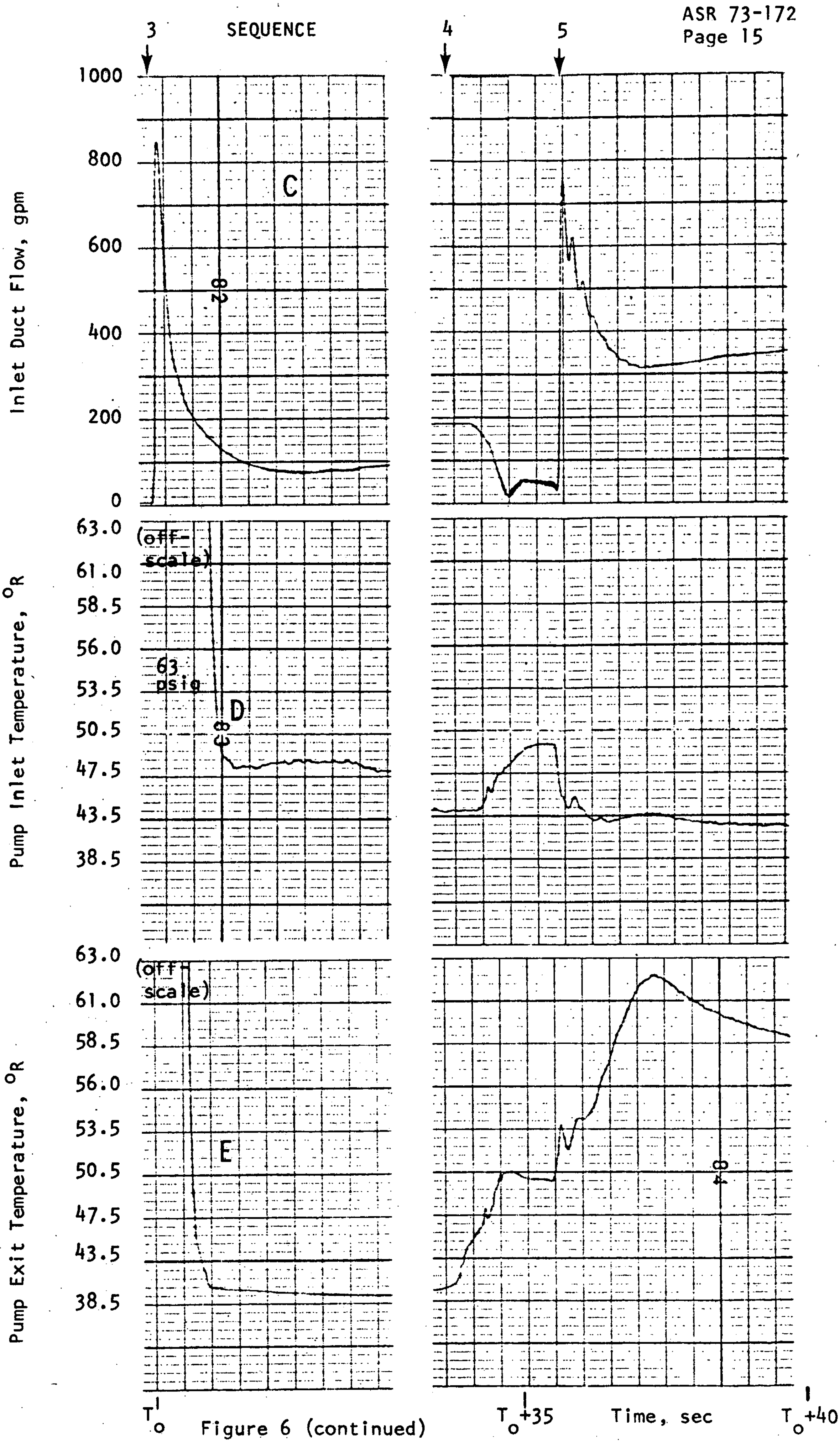

Figure 6 (continued)

It is conceivable that the first two tests were unsuccessful because of propellant conditions which resulted from closing the chill system valve rather than being the result of lesser degrees of pre-chill prior to pump rotation. It is significant to note that the third test started successfully with an inlet temperature of 50°R (the temperature which existed after the chill system valve was closed). Figures 1d and 1e show the pump inlet and exit hydrogen temperatures were chilled from ambient conditions to less than 50 and 40°R, respectively, in less than ten seconds. With an automated sequence to prevent a reduction in the chill flow immedaitely preceding pump rotation, it is speculated this test may have started successfully.

The other four coated feed system tests were under deadhead conditions. The results are not directly relatable to the uncoated system tests, however, because the coated pump generates significantly less head. The coated pump was started under deadhead conditions with a discharge pressure of 400 psig used to initiate opening of the throttle valve. A summary of the uncoated system tests is presented in Table 1.

Table 1. Summary of Coated Feed System Tests

Purpose	Test Number	Inlet Pressure (psig)	Valve Trigger Pressure (psig)	Discharge Volume (cu.ft)	Comments
Chill to 100%	24	72	NA	NA	Acceptable data
Pump Performance	25	65	Valve Open	3.45	Acceptable data, Double rpm indicated (wrong number of gear teeth assumed)
Pump Performance	26	65	Valve Open	3.45	Acceptable data
Nominal Start Conditions	27	65	Valve Open	3.45	Acceptable data
Start With Partial Chill	28a	65	Valve Open	3.45	Pre-start cut (incorrect valve position detect)
Start With Partial Chill (Intermediate Chill)	28b	65	Valve Open	3.45	Breakdown in developed head, Overspeed cut
Start With Partial Chill (Least Chilled)	30	65	Valve Open	3.45	Breakdown in developed head, Overspeed cut
Start With Partial Chill (Most Chilled)	31	65	Valve Open	3.45	Acceptable start
Deadhead Start With 100% Chill	29	65	600	3.45	Breakdown in developed head (trigger pressure set higher than nominal discharge pressure),Overspeed cut
Deadhead Start with 100% Chill	32	65	600	3.45	Breakdown in developed head (trigger pressure set higher than nominal discharge pressure), Overspeed cut
Deadhead Start With 100% Chill	33	65	500	3.45	Breakdown in developed head (trigger pressuer set higher than nominal discharge pressure), Overspeed cut
Deadhead Start With 100% Chill	34	65	400	3.45	Acceptable start

PLANNED EFFORT

Work has been completed as shown in Fig. 7. Writing of the draft copy of the final report has been initiated and will continue.

EXPENDITURES

A total of approximately 7250 hours and $197,910 have been expended, including materials.

Revised Schedule (Approved 10 October 1972)

Original schedule - Completed Tasks

Figure 7. Schedule for LH_2 Turbopump Rapid Start Program (Contract NAS8-27608)